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DEVELOPMENT OF THE VOLT-A SHUTTLE EXPERIMENT

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ABSTRACT

The NASA Lewis Research Center (LeRC) is investigating potential problems associated with the operation of high voltage solar cell arrays in the space plasma environment. At high voltages, interactions between the solar array and the space plasma could result in unacceptable levels of electrical discharge (arcing) and/or parasitic losses (current drains from the array to the plasma). The objective of the Voltage Operating Limit Tests (VOLT-A) Shuttle bay experiment is to characterize space plasma/solar cell panel interactions in low earth orbit. VOLT-A consists of an experiment plate subassembly which contains four solar panels, an electronics subassembly and a Langmuir probe subassembly mounted on an MPESS carrier. During a given 8.25 hour data taking period (5-1/2 continuous orbits), the solar panels, which represent state-of-the-art solar cell technologies, will be sequentially subjected to bias voltages in steps ranging from minus 626 V to plus 313 V. Appropriate measurements will be made at each voltage to characterize arcing and parasitic losses. Corresponding measurements of the plasma environment (plasma density, electron temperature and neutral density) will also be made. Data will be recorded on an on-board tape recorder for subsequent data reduction and analysis.

INTRODUCTION

The Voltage Operating Limit Tests (VOLT-A) Shuttle experiment is the flight test component of an overall environmental interactions (EI) program being conducted by the NASA Lewis Research Center (LeRC). The objective of the EI program, which also includes ground testing and analytical modelling, is to develop design criteria for spacecraft which operate in the low Earth orbit (LEO) space plasma environment. Systems of interest include solar arrays, power system conductors and insulators, and other exposed components. Surface-plasma interactions include current drains, charge buildup on insulators, and discharges to or through the space plasma. This paper presents the rationale, approach, and development status of the VOLT-A flight experiment including a brief description of the electrical and mechanical configuration, the mission requirements and the flight hardware qualification test program.

BACKGROUND

Since the early 70's, LeRC has been investigating the potential problems associated with the operation of high voltage solar cell arrays in the space plasma environment. For multi-hundred kilowatt power systems, solar array voltages higher than those typically used (e.g., 28 V) are required to minimize area and weight penalties associated with high currents (i.e., due to resistive losses in cabling, power processing inefficiencies, etc.). However, at the higher voltages, interactions between the solar array and the space plasma could result in unacceptable levels of electrical discharge (arcing) and/or parasitic losses (current drains from the array to the plasma). LeRC efforts in this area have involved analytical modelling, ground testing and flight experiments. Modelling efforts to date have had limited success due to the lack of adequate space data. Two EI flight experiments have been flown to date under the LeRC EI program, viz., the Plasma Interaction Experiments (PIX I and PIX II). The VOLT-A Shuttle bay experiment discussed herein is an extension of the earlier flight experiments and is designed to expand the EI data base.

PIX I, launched in 1978, demonstrated that arcing from the solar cell panel (hereafter called solar panel) into the plasma, which had previously been observed in ground tests, also occurred in space. PIX II, launched in 1983 as an auxiliary payload on the IRAS mission, extended this investigation by examining the effects of solar panel area on the plasma interactions. Arcing observed on PIX II occurred at significantly lower voltages than that measured on PIX I or in ground tests. PIX II also verified the importance of the plasma ram/wake effects and provided data on the arcing rates for 2 x 2 centimeter solar cells. It is important to note that no adequate theory describing the above-mentioned arcing has been developed to date. Both PIX flight tests were "piggyback" experiments placed in polar orbit at approximately 900 kilometers altitude, where plasma densities are relatively low, and employed solar panels having areas up to 2000 square centimeters biased by a programmable power supply. Due to several factors (limited mission time, low plasma density, minimal diagnostic instrumentation), it was deemed appropriate to refly a modified version of the

PIX II experiment in a denser equatorial plasma. This new experiment, known as VOLT-A, employs a significant amount of PIX II flight hardware. The primary objective of the VOLT-A experiment is to acquire and analyze data on interactions between high voltage solar panels and the space plasma environment to enable development of design criteria for future high power solar cell arrays. This will be accomplished by exposing various solar panels, biased to high voltages, to a measured space environment in a Shuttle bay experiment. The experiment will include an investigation of ram/wake effects on operating state-of-the-art solar pane .

LEO ENVIRONMENT

In low Earth orbit (LEO), the space environment contains neutral atoms and molecules (the residual atmosphere), plasma (ionized atoms and electrons), a magnetic field, and radiation and charged particles from the sun and other extraterrestrial sources. Plasma density as a function of altitude for this region is shown in Figure 1. The plasma density peaks in the range of 10^5 to 10^6 particles per cubic centimeter at 300 km (Shuttle Orbiter altitude). Higher densities during daytime conditions and during periods of maximum solar activity occur due to photoionization of the residual atmosphere by solar radiation. Densities of the neutral and ionized atmosphere can vary by two orders of magnitude or more depending on these conditions. For a large space structure such as space station, system generated effects may also be important. The station's power system may involve high voltages and currents (leading to electric and magnetic fields), effluents from possible sparking events and outgassing. In addition, waste and water dumps, attitude control thruster firings and reboost firings will dramatically increase the neutral atmosphere density near the station.

As indicated in Figure 1, the plasma (ion or electron) density in the region of a space station at 500 kilometers is expected to vary from about 4×10^4 to more than 10^6 particles per cubic centimeter. Densities corresponding to the proposed VOLT experiment, the PIX II experiment and tank tests are shown for comparison.

RATIONALE FOR VOLT EXPERIMENT

As noted earlier, multi-hundred kilowatt solar arrays in LEO must be operated at voltages much higher than 28 volts to minimize losses in power distribution and power processing elements of the system. Such an array, like any system in a plasma environment, will come to equilibrium with the environment by acquiring potentials and collecting currents such that the net current to the system is zero. This process establishes array potentials relative to plasma ground. Because electrons are much more mobile than ions, the array with its impressed voltage differences will float electrically with an area at negative potentials relative to plasma ground (for ion collection) much larger than its positive area (for electron collection); for example, 90 percent negative and 10 percent positive. Therefore, at high negative bias relative to the plasma potential, the large arrays might be vulnerable to arcing in the dense LEO plasma, while at high positive bias, plasma drain currents could lead to high power losses. It is therefore essential for the proper design of the solar array power system that realistic safe voltage operating limits be established.

Sufficient data for designing high power, high voltage solar arrays currently do not exist. Ground-based tests in vacuum tanks reveal arcing and parasitic losses, but the results may be affected by the finite tank volumes and unrealistic electron temperatures in these simulations. Spaceflight experiments PIX I and PIX II operated in the relatively low plasma densities found at high altitudes, and experienced important effects (e.g., ram/wake effects on PIX II) which cannot be simulated in the laboratory. Arcing and plasma drain current measurements from PIX II extrapolated to expected space station plasma densities assuming a 500 km orbit are shown in Figures 2 and 3, respectively, It is important to note that such extrapolations involve a high degree of uncertainty. Hence, further measurements in LEO are necessary to generate the data that design engineers will need in planning, laying out, and specifying the operating characteristics (voltage limits, series string configurations, cell types) of high power, high voltage solar arrays.

VOLT-A GENERAL DESCRIPTION

The VOLT-A Shuttle bay experiment consists of three subassemblies, viz., an experiment plate, a Langmuir probe plate and an electronic subassembly, mounted on an MPESS (mission-peculiar experiment support structure) carrier. The VOLT-A basic electrical circuit is shown schematically in Figure 4 while a sketch of the physical configuration is shown in Figure 5. The experiment involves four small electrically-loaded solar panels which are sequentially subjected to bias voltages in steps ranging from minus 626 volts to plus 313 volts, while measurements of plasma interactions (arc rate and arc magnitude and magnitude of plasma drain currents) are made and stored on an on-board tape recorder. The solar panels will be placed in various orientations relative to the sun and to the ram direction using the Shuttle Orbiter attitude control system. Diagnostic instruments include a sun sensor which provides solar insolation data, spherical and cylindrical Langmuir probes to enable

determination of plasma density and temperature and vehicle potential, and a vacuum gauge to measure neutral particle density, both background and perturbed by the Shuttle Orbiter. The VOLT-A subassemblies are described in more detail below:

Experiment Plate Subassembly

The experiment plate subassembly is designed as a table which places the plane of solar panels above the Orbiter sill level. For electrical isolation, the resistance between each panel and between the panels and ground is $> 10^{11}$ ohms. The capacitance to vehicle ground is 2000 to 2500 pF. Three of the four solar panels contain twenty-eight series connected 5.9 x 5.9 cm silicon solar cells, attached through a Kapton sheet to a rigidized aluminum plate. One of the three panels contains solar cells with gridded back contacts and welded interconnects on the back and oriented with the active side (blue side) up. The second panel, identical to the first, is oriented blue side down. This will enable evaluation of plasma interactions on both the top and bottom of flexible deployable-type solar arrays. The third solar panel contains 5.9 x 5.9 cm cells employing conventional backing (nongridded) and conventional top to bottom contacts, mounted blue side up. The fourth solar panel, from the PIX II experiment, contains 456 2 x 2 cm silicon cells with standard contacts. This panel is configured as an array of six strings in parallel, each string having 76 cells in series. This solar panel, having a well-documented history in terms of flight and ground testing, will allow comparison and calibration. The experiment plate subassembly also contains the sun sensor described earlier.

Langmuir Probe Plate Subassembly

The Langmuir probe plate subassembly consists of an "L" shaped bracket attached to the top of the MPESS carrier and positioned about 13 inches from the experiment plate. A 15-inch high mast is located at each corner of the bracket. One mast holds the spherical Langmuir probe which consists of a 1/2 inch diameter gold plated brass ball. The cylindrical Langmuir probe is a spring-loaded 20 mil diameter phosphor/bronze wire, 70 cm long, stretched between the other two masts.

Electronics Subassembly

The electronics subassembly is mounted on the side of the MPESS carrier below the experiment plate. All electronic instruments are mounted on a plate and contained within an enclosure. The enclosure provides support for a multilayer insulation blanket as well as EMI protection. In addition, a vacuum gauge (cold cathode type) is located in the electronics enclosure with its nozzle extending through the side to measure the neutral particle density in the vicinity of the experiment.

Five of the electrical boxes are modified versions of backup flight hardware from the PIX II experiment, viz., electrometer, high voltage power supply, power control unit, sequencer/multiplexer and Langmuir electronics. The vacuum gauge and tape recorder are commercially available flight qualified units. The input filter and heater control, and the transient current detector were specifically designed, built, and tested for VOLT-A. The location of the electronic devices on the electronics plate is shown in Figure 6. The electronics plate also contains surface mounted strip heaters which are thermostatically controlled to maintain temperatures within the design range.

MISSION AND DATA REQUIREMENTS

The VOLT-A project, conceived as a low cost Shuttle Orbiter bay experiment, was to utilize a significant amount of backup PIX II flight hardware, modified as necessary. Furthermore, it was deemed prudent to minimize experiment time and space requirements to facilitate manifesting on the Shuttle. At the same time, system designers were aware of the need for meaningful data which could be readily extrapolated in terms of cell design, voltage and time. Based on the above, the mission and data requirements shown in Tables 1 and 2, respectively, were established.

To obtain statistically significant data, measurements are required over a range of bias voltages. Furthermore, each voltage must be applied for a sufficient length of time. Since the LEO environment is constantly changing in terms of plasma density and temperature, plasma parameter measurements must be made relatively frequently. As noted earlier, ram/wake, as well as sun/antisun conditions are also of interest. Based on the above, the VOLT-A experiment timelines shown in Figures 7a and 7b were established.

The VOLT-A experiment was designed to meet the above mentioned requirements and is expected to determine:

1. How strong the arcs are and at what voltage and frequency they occur.
2. How the arcs are changed by solar cell design changes.
3. What effect wake conditions have on plasma current collection.
4. What effect impressed potentials have on the vehicle potential.

A summary of the measurements to be made on VOLT-A is given in Table 3.

TABLE 1 - VOLT-A MISSION REQUIREMENTS SUMMARY

- VOLT experiment mounted across the bay on MPESS carrier.
- 5-1/2 continuous orbits and 7 attitude changes per data take; attitude changes accomplished within 2 min.
- Three data takes during 7-day mission.
- Cylindrical free space: 3.4 m O.D. by 1 m high centered on experiment plate surface.
- 160 nmi orbit; 28.5° inclination.
- 48 hour outgassing prior to activation of VOLT-A.
- 100 watts, 28 volt DC power; 15 kW-hr energy.
- Access to switch panel; turn experiment on/off noting time.
- Must accommodate high EMI levels.
- Observe/photograph arcs.

TABLE 2 - DATA TAKING REQUIREMENTS SUMMARY

- Unbiased solar panels segments must be grounded.
- Voltage on arrays must be zero during Langmuir probe sweeps.
- Langmuir probe sweeps must be done ≤ 2 minutes apart to keep track of changing plasma conditions in orbit and in time.
- Arcing data must be obtained with ≥ 2 minutes per voltage to allow for possible time necessary for arcing conditions to develop. $V \approx -200$ volts very important.
- Collection currents must be measured over a wide voltage range of positive and negative biases.
- Wake conditions must be bracketed by ram conditions to find a baseline for the ambient plasma.
- All solar panels must be tested for arcing and collection currents.

TABLE 3 - VOLT-A MEASUREMENTS SUMMARY

- Collection currents.
- Load currents.
- Load transients.
- Arc rates.
- Plasma densities and temperatures.
- Neutral density
- Sun angle

ELECTRICAL SYSTEM DESCRIPTION

The VOLT-A electrical system is essentially self-contained except for 28 volt DC power and on-off switching. These functions are provided through the Shuttle carrier harness which integrates the VOLT-A electronics with the Shuttle. In addition, a ground support equipment (GSE) harness is provided which permits monitoring of the real-time data stream during ground testing and recovering of stored data from the flight tape recorder after the flight experiment is completed.

A simplified functional block diagram of the VOLT-A electrical system is shown in Figure 8. It should be noted that certain electronic components provide more than one function. For example, the sequencer/multiplexer component provides the program sequence control, data multiplexing, sun sensor signal conditioning and short-term data storage. For convenience, each of these functions is separated in the block diagram.

Shuttle Orbiter Interface

The VOLT-A electrical system contains all the electronics needed to perform the flight experiment and to satisfy the interface requirements relative to the Shuttle Orbiter. The electronics boxes operate from 28 volt DC Orbiter power. The crew member conducting the experiment selects the OFF/STANDBY/ON modes of operation from the Orbiter standard switch panel according to the flight schedule. The VOLT-A electrical system provides status signals for display at the switch panel so that the crew member can confirm the appropriate mode of operation.

Input Filter and Heater Control

Orbiter power, commands and display signals interface with the VOLT-A electronics at the input filter and heater control box. This component provides EMI filtering for all wiring to the Orbiter. In the OFF mode, with 28 volt DC power available, one heater circuit is energized to maintain minimal temperature conditions within the enclosure. The STANDBY mode is selected after reaching orbit. At that time, three additional heater circuits are energized and set to maintain the enclosure temperature at 70 °F ± 5 °F. The standby heaters are disabled when the VOLT-A experiment is switched to the ON mode and the electronics components are energized, primarily to minimize EMI with the internal electronic circuits.

In the ON mode, the Power Control Unit (PCU) is turned on. Its circuits generate and control the various mix of voltages and power needed to operate the other electronic components. The PCU provides 28 volts DC (VDC), ± 15 VDC, 5 VDC and 25 kHz AC power.

Program Sequencer

The program sequencer is a Programmable Read Only Memory (PROM) controller. It is preprogrammed prior to launch to provide the desired flight experiment configuration, sequence of events and voltage levels. When power is applied, the PROM is read every 8 seconds to update the experiment. Any time

power is removed, it will automatically reset to its initial conditions.

Basic Experiment/Solar Panel Interface

The high voltage power supply generates a programmed sequence of voltage levels (positive and negative) which is applied to each of the solar panels. Only one of the four panels can be biased at a given time as determined by the array configuration relays. The electrometers monitor currents that occur due to the solar panel/plasma interactions. The high voltage bias connecting point is at the center tap of the solar panels to provide symmetry for both positive and negative bias. Unbiased panels are grounded by bleeder resistors to prevent buildup or storage of charges on the panels.

Each solar panel has a resistive load equal to half-maximum power impedance on the high voltage side. The three active panels have voltage sensors monitoring the output voltage generated at the load resistors.

Arcing could cause perturbations in the solar panel load circuits. A current probe monitors current perturbations and the transient current detector counts those current transients that exceed 10 ma and 20 ma as part of the experiment. Arcing could also cause perturbations in the high voltage power supply or overload shutdowns. This information is also processed and counted by the transient current detector.

Diagnostic Instruments

The four diagnostic instruments used on VOLT-A are discussed below. A vacuum measurement system, which monitors the background pressure in the Orbiter bay, is positioned with its nozzle extending through the side of the enclosure and thermal blanket. The gauge and its electronics are incorporated within the electronics enclosure.

Two Langmuir probes are mounted on top of the MPESS carrier near the experiment plate. The cylindrical probe has a scan voltage mode whereas the spherical probe operates at a fixed voltage. Plasma density and electron temperature information can be determined by these probes. The Langmuir electronics mounted within the enclosure provides the electrical input for these probes.

A sun sensor mounted on the experiment plate subassembly will provide sun angle information. Its electronics for signal conditioning are incorporated within the sequencer/multiplexer.

Data

The data multiplexer sequentially scans the various analog and digital signals generated by the electronic components and compiles this information digitally. The data is formulated into a serial NRZ-L PCM compatible stream, inserting all necessary frame sync and subframe identifiers. The data stream rate is 128 bits per second BPS.

The data are stored for a short term in dynamic random access memories, DRAMS, to provide approximately 262 K bits or 34 minutes of data. When the storage is full, the oldest data is overwritten automatically.

Every 15 minutes, the tape recorder is turned on by the program sequencer and the data stored in DRAMS are read out of the memory at a 4096 BPS rate and recorded in the flight magnetic tape recorder. The rates and times are selected so that each data word is actually recorded up to four times in the flight experiment. After the flight experiment is returned from space, the VOLT-A GSE will recover the magnetic tape recorder data for analysis. Since each data word is recorded at least three times, it will be possible to employ majority voting schemes should data discrepancies occur for any reason.

MECHANICAL DESIGN AND ENVIRONMENTAL TESTING

The VOLT-A mechanical design requirements were established based on experimental, environmental and safety/system considerations. The experiment requirements dictated such items as the size of the wire for the cylindrical Langmuir probe as well as the diameter of the ball for the spherical Langmuir probe. The minimum distance from other conducting surfaces was also stipulated. The size, type, and quantity of solar cells influenced the size of the mounting plate used to support the cells. Furthermore, the solar panels were to have an unobstructed viewing angle to the space environment. This detail required the solar panels mounting plate to be supported some distance from the MPESS. The plane of solar panels had to be placed above the sides of the Orbiter bay thus providing a clear view to space. In addition, the electronics needed to run the experiment dictated the overall size of the structure required to house them.

The structural requirements involve two aspects: (1) environmental loads imposed on the experiment hardware during the flight, and (2) the effects of the experiment hardware on the Orbiter environment. The loads imposed on the structures include: vibrational-sinusoidal and random, acoustic noise - during ascent, quasi-static - low frequency accelerations, and thermal - on orbit and landing. The major areas of concern related to the equipment's effect on its environment are EMI production and outgassing. The outgassing is of particular concern due to its effect on the plasma density.

The safety/system requirements can be considered "all encompassing" for they relate to the safety and integrity of the STS and its crew. In essence, the experiment and related hardware are, in no way, to compromise the integrity of the Orbiter and therefore the safety of the crew.

Description of Structural System Components/Materials

The material used for a majority of the components is aluminum 6061-T6.

The Langmuir probe assembly consists of three probe masts and an "L" shaped base to which they are attached. The masts are constructed of 1" square aluminum tubing welded to a 2" x 2" x 1/4" baseplate which is mechanically fastened to the "L" shaped base. The masts are topped with a micarta insert to support the probe and isolate them from the surrounding conducting surfaces. The "L" shaped base is constructed of 2" square aluminum welded at the ends to aluminum angles. This structure bridges the top rails of the MPESS and is mechanically fastened to them. The experiment mounting plate is fabricated from 0.5 inch aluminum plate and mechanically fastened to four support legs which are machined from solid aluminum blocks to hollow cylinders with rectangular end flanges. The legs are mechanically fastened to the MPESS cross beams. The cross beams are extruded aluminum "I" beams fitted across the top rails of the MPESS carrier and mechanically fastened to them.

The electronic subassembly consists of a mounting plate for the electronic components and a cover. The cover is fabricated from 0.063 inch thick aluminum sheets and joined by rivets. The cover is mechanically fastened to the mounting plate. The mounting plate is fabricated from 0.5 inch thick aluminum plate and mechanically fastened to the MPESS carrier.

Preliminary Design Calculations

A summary of preliminary design calculations is presented in Table 4. The calculations are based on accepted analytical procedures with the loading conditions extracted from appropriate NSTS documents. The results give a general idea as to the integrity of the structure and compliance with design requirements.

TABLE 4 - DESIGN CALCULATIONS SUMMARY

	Natural frequency, fn (Hz)
Langmuir probe subassembly	60
Experiment plate subassembly	50
Electronic subassembly	52

Minimum design limit = 35 Hz

Worst case lift off plus random	Design limit load factors, g's Direction x_o	y_o	z_o
Langmuir probe subassembly	+14/-11.5	$\pm$ 11.9	$\pm$ 15.1
Experiment plate & electronics subassembly	+11.8/-9.3	$\pm$ 9.7	$\pm$ 12.9

Environmental Testing

A general description of the type of environmental tests applicable to the VOLT-A hardware is given below:

Vibration Testing - There are two levels of vibration testing, viz., qualification and acceptance. The qualification level is to verify the structural integrity of the configuration and applied only to the prototype/backup models. The acceptance levels are applied only to flight models, that is, a workmanship vibration test. The acceptance levels are 6dB below the qualification levels and both include sinusoidal and random vibration levels. The vibration tests are also used to verify the natural frequency of the structures.

Thermal/Vacuum Testing - These tests are used to check the structural and system integrity during on-orbit thermal excursions. They are also used to verify the thermal model.

Acoustic Testing - A check of system susceptibility to acoustic vibrational levels experienced during ascent will be made.

EMI - Electromagnetic Interference Testing - A test to evaluate the levels of EMI produced from the experiment during operation will be conducted.

Outgassing Testing - The types of gas coming off the hardware during the on-orbit vacuum and temperature conditions will be monitored during the outgassing test.

Additional Testing/Analysis

The following items are also included as part of the requirements for mechanical design/environmental testing.

Calibration Testing - A baseline calibration will be performed on the sun sensor, vacuum gauge, Langmuir probes, solar panels and the complete system. These will be used to evaluate the performance of the system before and after the flight.

Structural Model - A NASTRAN model was used to further evaluate the structural integrity of the experiment subassemblies.

Fracture Control Plan - A mission-specific Fracture Control Plan (FCP) will be developed which addresses each component (piece part, fasteners and welds) forming the structural configurations for this experiment. The FCP shall document the following items:

(1) A list of those "exempt" components screened from fracture control considerations together with all rationale, analyses and supporting data.

(2) A list of "nonfracture critical" and "fracture critical" components with rationale, analyses and supporting data for their classification and inspection requirements.

VOLT-A DEVELOPMENT STATUS

At this writing, all components comprising the electronic subassembly have been fabricated, tested, and mounted on the electronics plate. The flight electronics subassembly is about to be subjected to thermal/vacuum testing. An engineering model of the Langmuir plate assembly has been fabricated and successfully tested to qualification levels.

Due to budget constraints, work on the VOLT-A experiment is currently being curtailed. During the remainder of CY 85, thermal/vacuum testing of the electronics subassembly will be completed. Continuation of the project in 1986 is contingent on securing additional funding.

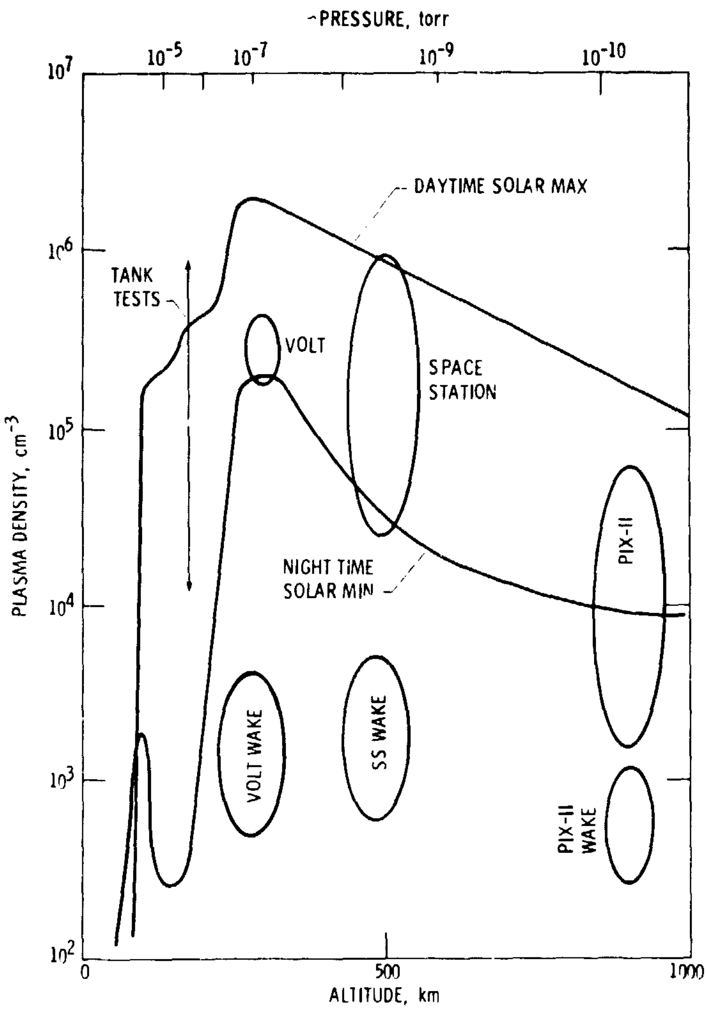


Figure 1. - Range of plasma densities in LEO.

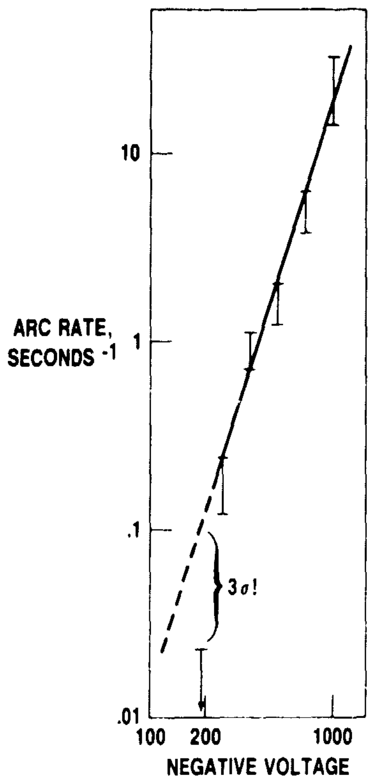


Figure 2. - Arc rate as a function of voltage from PIX II-normalized to expected plasma densities at 500 km near solar maximum.

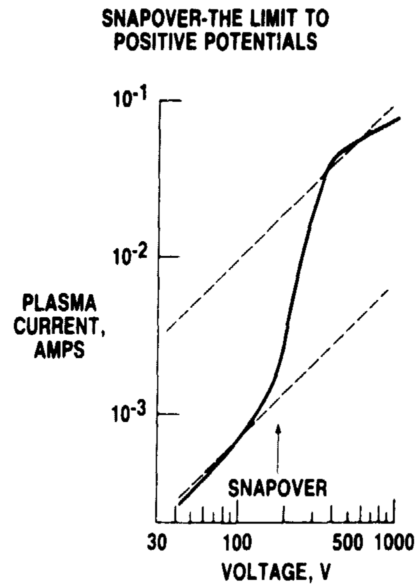


Figure 3. - Plasma current as a function of voltage from PIX II-normalized to expected plasma densities at 500 km near solar maximum.

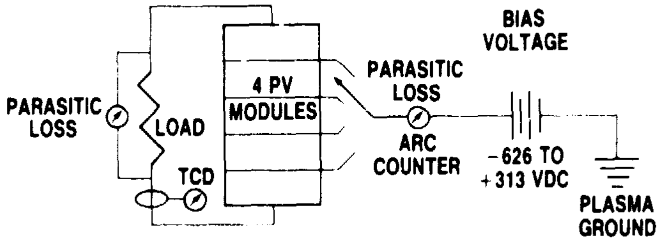


Figure 4. - VOLT-A system block diagram.

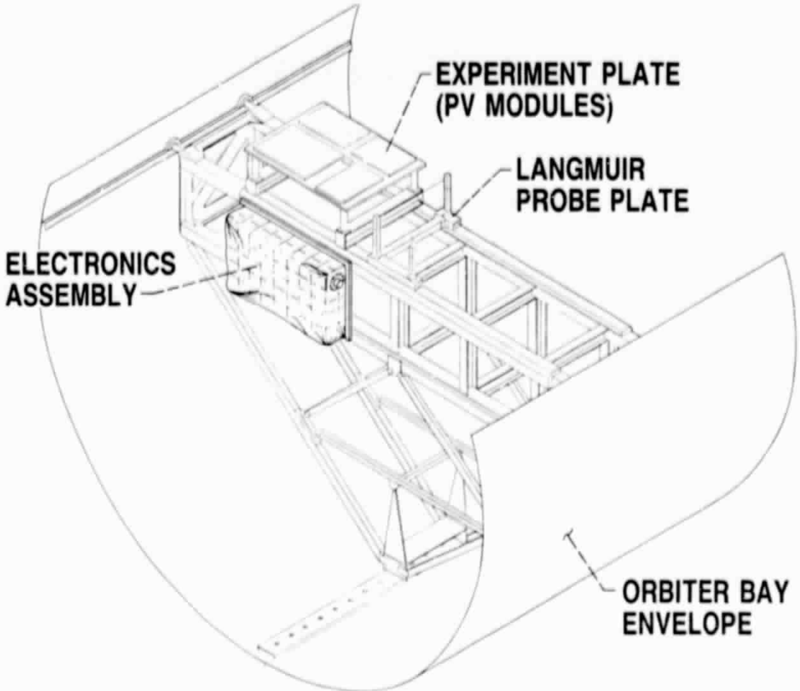


Figure 5. - VOLT-A mounted on MPESS carrier.

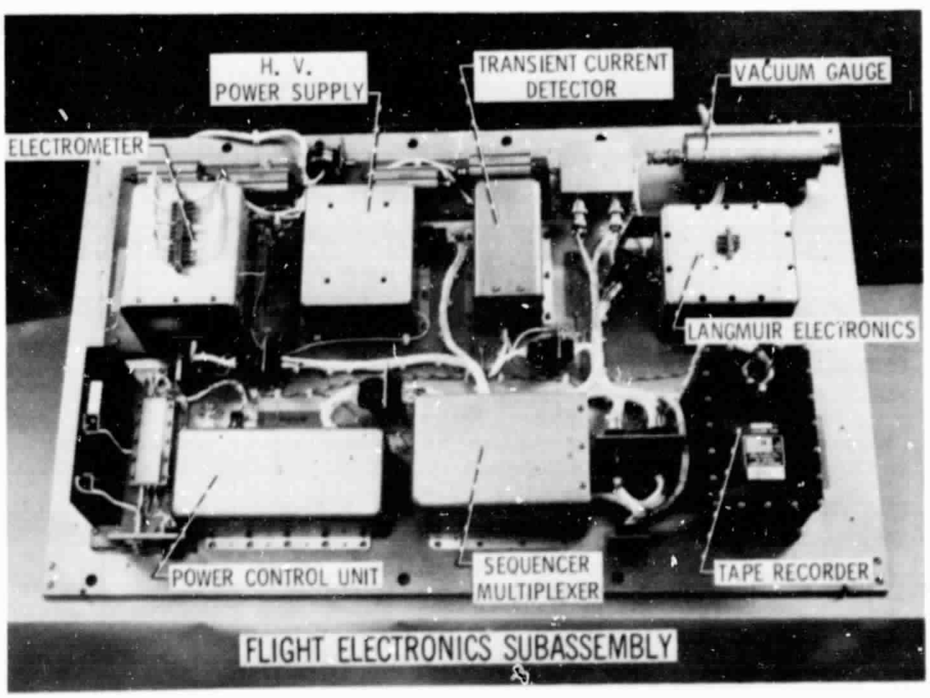
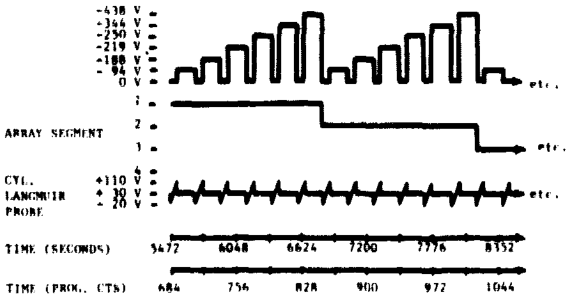
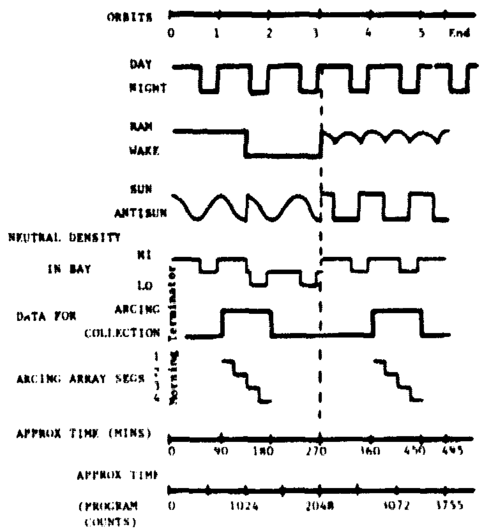


Figure 6. - VOLT-A flight hardware.



(a) Short timescale.



(b) Long timescales.

Figure 7. - VOLT-A timeline.

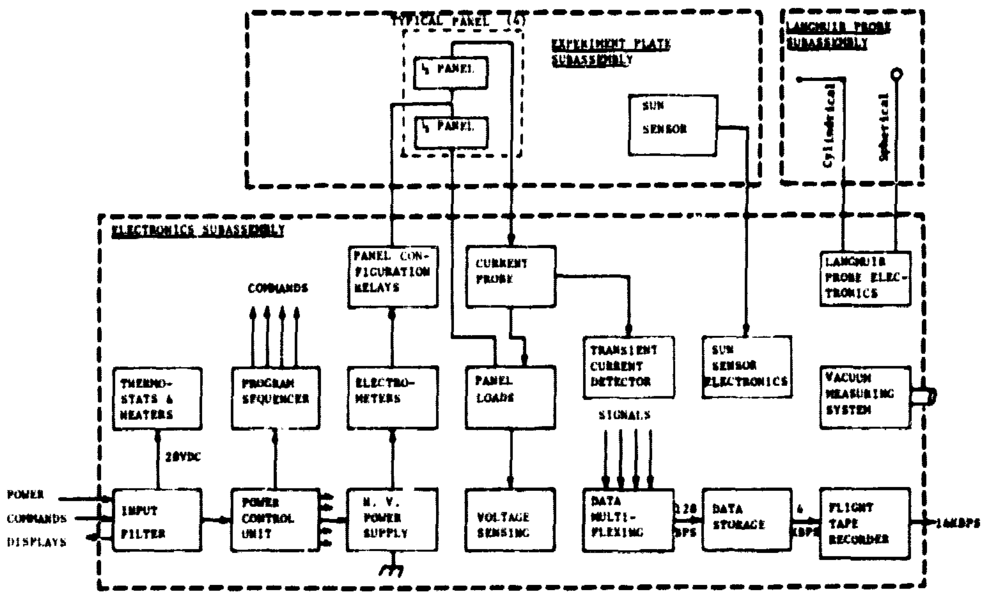


Figure 8. - VOLT-A electrical system functional block diagram.

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16. Abstract

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